Color dimensions of additive manufactured interim restorative dental material

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Abstract: STATEMENT OF PROBLEM Interim dental restorations can be fabricated by using additive manufacturing (AM) technologies. Although dental restoration contours can be easily and accurately fabricated by using computer-aided design (CAD) procedures, protocols for creating predictable color dimensions of AM interim restorations are lacking. PURPOSE The purpose of this in vitro study was to measure and compare color dimensions of different AM and conventional interim restorative materials. MATERIAL AND METHODS Disks (N=420) were fabricated by using either conventionally (CNV group) or additively manufactured (AM group) materials. The CNV group was further divided into the subgroups CNV-1 (Protemp 4; 3M ESPE) and CNV-2 (Anaxdent new outline dentin; Anaxdent). AM subgroups included AM-1 (FreePrint temp; Detax), AM-2 (E-Dent 400; Envisiontec), AM-3 (NextDent CB; NextDent), AM-4 (NextDent CB MFH; NextDent), and AM-5 (Med620 VEROGlaze; Stratasys). Color measurements in the CIELab coordinates were made by using a spectrophotometer (VITA EasyShade Advance 4.0; VITA) with a standardized photography gray card as a background under room light conditions (1003 lux). Color difference (ΔE*) values were calculated by using the CIE76 and CIEDE2000 formulas. The data were analyzed by using the Kruskal-Wallis test with nonparametric pairwise comparisons. RESULTS Owing to a software error, the spectrophotometer was unable to measure the color of any specimens in the AM-5 subgroup, which was consequently excluded from further analysis. Significant differences (P=.001) between 2 manufacturing groups were found based on the L* variable. All subgroups were significantly different from each other for all 3 variables (P<.001). Pairwise comparisons revealed that all groups were significantly different from each other, except for the AM-1 and AM-2 subgroups, compared with the CNV-1 subgroup for the L* color dimension. The ΔE* values calculated by using the CIE76 formula varied from 6.63 to 23.1 and by using the CIEDE2000 formula from 3.43 to 10.21, suggesting a perceptible and unacceptable color mismatch between the CNV and AM groups. CONCLUSIONS None of the additively manufactured interim materials tested matched the conventional interim materials in all 3 CIELab color dimensions.

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Color dimensions of additive manufactured interim restorative dental material.

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ABSTRACT

Statement of problem. Interim dental restorations can be fabricated using additive manufacturing (AM) technologies. Although dental restoration contours can be easily and accurately fabricated using computer aided design (CAD) procedures, protocols for creating predictable color dimensions of AM interim restorations are lacking.

Purpose. The purpose of this in vitro study was to measure and compare color dimensions of different AM and conventional interim restorative materials.

Material and methods. Disks (N=420) were fabricated using either conventionally (CNV group) or additively manufactured (AM group) materials. The CNV group was further divided into the subgroups CNV-1(Protemp 4; 3M ESPE) and CNV-2 (Anaxdent new outline dentin; Anaxdent). AM subgroups included AM-1 (FreePrint temp; Detax), AM-2 (E-Dent 400; Envisiontec), AM-3 (NextDent C&B; NextDent), AM-4 (NextDent C&B MFH; NextDent), and AM-5 (Med620 VEROGlaze; Stratasys). Color measurements in the CIELab coordinates were made with a spectrophotometer (Vita EasyShade Advance 4.0; Vita) using a standardized photography gray card as a background under room light conditions (1003 lux). Color difference (ΔE^*) values were calculated using the CIE76 and CIEDE2000 formulas. The data were analyzed using the Kruskal-Wallis test with nonparametric pairwise comparisons.

Results. Due to a software error, the spectrophotometer was unable to measure the color of any specimens in the AM-5 subgroup, which was consequently excluded from further analysis. Significant differences (P=.001) between 2 manufacturing groups were found based on the L* variable. All subgroups were significantly different from each other for all 3 variables (P< .001). Pairwise comparisons revealed that all groups were significantly different from each other, except for the AM-1 and AM-2 subgroups compared with the CNV-1 subgroup for the L* color dimension. The ΔE* values calculated using the CIE76 formula varied from 6.63 to 23.1 and using the CIEDE2000 formula from 3.43 to 10.21, suggesting a perceptible and unacceptable color mismatch between the CNV and AM groups.

Conclusions. None of the additively manufactured interim materials tested matched the conventional interim materials in all 3 CIELab color dimensions.

CLINICAL IMPLICATIONS

Color matching with AM interim dental materials can be difficult, as the protocol and properties of the materials used significantly differ from those of conventionally fabricated interim restorations. Custom shade guides are recommended to produce AM interim restorations with the desired shades predictably.

INTRODUCTION

Successful esthetic dental restorations depend on the ability to match the shape and the shade of the natural dentition.[1,2] Computer-aided design (CAD) technologies are able to match the contralateral tooth shape using software, allowing the dental technician to design the interim restoration in a predictable manner. However, replicating the color of the natural dentition presents challenges.[3-6]

Additive manufacturing (AM) procedures provide an alternative manufacturing method of fabricating interim dental restorations[7-10] in which a powder or liquid base material is solidified to form a 3D object.[11-20] Various polymers can be selected to fabricate AM interim dental restorations.[14] However, information regarding the esthetic, mechanical, and optical properties of these 3D-printed interim materials is lacking.[21,22]

Accurate perception of color discrepancies depends on the experience and training of the observers. The shade of the definitive restoration depends on accurate shade selection and communication between the dentist and technician, the dental technician's skill in handling restorative materials, and the ability of the restorative material to mimic tooth color after processing.[1,6]

The CIELab system is frequently used in dentistry to quantify tooth color.[23] Data obtained from computerized colorimetry or spectrophotometry allow for mathematical comparison of color properties.[23,24] Dental spectrophotometers can be also used to analyze color dimensions in the CIELab coordinates.[25-37] Attempts to measure the perceptibility and acceptability of color differences based on ΔE^* using the CIE76 formula have been published.[33-43] Perceptible ΔE values of 1,[38] 2.2,[42] or 3.7 have been reported[43] with acceptable color difference values from 2.72 to 6.8.[23,24,38,43,44] Recent publications have described a more sophisticated color difference formula that more precisely describes human perception, the CIEDE2000 formula.[45] However, the thresholds of perceptible and acceptable color differences using this new formula have not yet been established.

The purpose of this in vitro study was to measure the color dimensions of different AM interim materials in the CIELab coordinates and compare them with those of conventional dental interim materials. The null hypotheses tested were that no significant difference in the L*, a*, and b* color dimensions would be found among the conventionally processed and AM groups of interim dental materials or between individual 3D-printed materials.

MATERIAL AND METHODS

Lack of information on the specimen variability precluded use of power analysis to determine the required specimen size. Furthermore, resource sharing with other projects determined that 60 specimens per material subgroup were fabricated (n=60). Since the specimen group was determined by the material used in its manufacture, no specimen randomization was possible. These disks were categorized into 2 general groups, namely conventional (CNV) and additive manufactured (AM) interim material groups (Table 1). For all groups, a match to the A3.5 shade was attempted by using the corresponding materials.

For specimen fabrication of the CNV group, a ceramic sampler (Porcelain sampler; Smile line) was used to fabricate an acrylic resin disk (Pattern resin; GC) of 10 mm in diameter and 2.2 mm in thickness. This acrylic resin disk was used to make a high viscosity polyvinyl siloxane (Lab Putty; Coltène) impression to fabricate the additional conventional specimens. Two subgroups were created within the CNV group: CNV-1, which used an autopolymerizing bis-acryl composite interim material (Protemp 4 temporization material, A3.5 color; 3M ESPE) and CNV-2, which used an autopolymerizing acrylic resin interim material (New outline Anaxdent, dentin A3.5 color; Anaxdent).

For the AM groups, a digital design of a disk with a 10-mm diameter and 2-mm thickness was created using open source software (Blender v2.77a; The Blender Foundation). The standard tessellation language (STL) file was used to manufacture all the AM specimens. Five AM subgroups (AM-1 to AM-5) were established based on different 3D-printing materials (Table 1).

For the AM-1, AM-3, and AM-4 groups, a DLP printer (Rapidshape D30; Rapidshape) with a 1920×1080-pixel resolution was used to fabricate the specimens following the manufacturer’s instructions. The printing materials for those groups were chosen to have wavelengths compatible with the printer.

For the AM-2 group, an SLA printer (Envisiontec VIDA printer; Envisiontec) with a XY resolution of 73 µm and Z resolution from 25 µm to 150 µm was used. The interim material (E-Dent 400, color A3.5, Envisiontec) disks were fabricated following the manufacturer's recommendations. For AM-5, a polyjet printer (Object Eden 260VS; Stratasys) with 16-µm resolution at the X-, Y-, and Z-axes was used to fabricate the specimens (Med620 VEROGlaze; Stratasys) following the manufacturer's instructions.

A polishing sequence of 180-, 320-, 600-, 800-, and 1400-grit SiC papers using a polishing machine (Streurs Rotopol 2; Struers) allowed standardization of the surface of all the disks and consistency of the final polish (Fig. 1). The final disk thickness of 2 mm was verified with digital calipers (Mitutoyo 500-196-20 6'' Digimatic digital caliper; Mitutoyo).

Color measurements in the CIELab coordinates of all the specimens were made with a spectrophotometer (VITA EasyShade Advance 4.0; Vita Zahnfabrik). The spectrophotometer was calibrated following the manufacturer's instructions before the measurements were made. A standardized photography neutral 18% grey card (Kodak Gray Cards; Tiffen Co) was used as a background for the shade measurements. The spectrophotometer probe tip was placed perpendicular to the center of the dry disk and held until completion of the measurement. The illuminance of the room was 1003 lux and was measured using a light meter (LX1330B Light Meter; Dr. Meter Digital Illuminance).

The L*, a*, and b* values for each specimen were measured 3 times and averaged before further analysis. The ΔE* value between material group averages was calculated using the CIE76 formula: $\Delta E_{ab} = [(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2]^{1/2}$. Same group differences were also calculated using the CIEDE2000 formula.[45]

To determine whether the variables were normally distributed, a 1-sample Kolmogorov-Smirnoff test was performed. The Bartlett test was used to determine whether the group and subgroup variances were homogeneous. Depending on the results of these 2 tests (α=.05), either a nonparametric Kruskal-Wallis test followed by nonparametric pairwise comparisons (a pairwise Dwass, Steel, Critchlow, Fligner test)[46] or a parametric ANOVA with post hoc pairwise comparisons was used to determine whether significant differences were present among the groups and which groups were different from each other. The ANOVA used nested treatment design to test for AM and CNV manufacturing and then further test for the differences among individual manufacturing materials. To test for the differences among overall AM and CNV groups using nonparametric statistics, all the AM and CNV groups were pooled into corresponding overall groups, and a Wilcoxon test was used to determine whether significant differences existed between the 2 groups for each variable. All statistical analyses were performed in R statistical environment.[47]

RESULTS

The spectrophotometer was unable to measure the color of all the specimens in the AM-5 group due to a spectrophotometer measurement error. Therefore, this group was excluded from the statistical analysis. The rest of the specimens were measured without any errors.

Means and standard deviations for the L*, a*, and b* measurements are presented in Table 2. The boxplots of the minimum, maximum, interquartile range, medians, and the outliers for each of the L*, a*, and b* variables are presented in Figure 2. The ΔE* values are presented in Table 3 and 4.

No consistent pattern was found across the 3 variables among the manufacturers. Based on the L* component, the AM-1, AM-2, AM-3 groups and CNV-1 group were consistent, and the AM-4 and, possibly, CNV-2 groups were the outliers. For component a*, AM-1 and AM-2 were similar to each other. Groups AM-3 and AM-4 were similar but had values below those for groups AM-1 and AM-2. Groups CNV-1 and CNV-2 occupied the opposite extremes of the a* value range. The pattern was different for the b* component, where AM-3 and AM-4 groups occupied the middle of the b* value range, while AM-1 and AM-2 groups occupied the opposite extremes of the b* value range.

After performing a Kolmogorov-Smirnoff test, the hypothesis of a normal distribution was not rejected for each group. The Bartlett test was rejected with $P<.001$ for all 3 variables, signifying that the variances of the groups were unequal and the classic analysis of variance for group comparison could not be used. This Bartlett test result also prevented the use of ANOVA with a nested treatment design to test for the differences between the AM and CNV groups in general. The Wilcoxon test of the overall difference between AM and CNV groups revealed that the AM and CNV groups were different for the L* variable: W=17385, $P=.001$, but not for the a* or b* variables (for a*: W=14450, $P=.958$; for b*: W=13998, $P=.667$). A nonparametric Kruskal-Wallis test was then used to determine whether the individual groups were significantly different from each other for the L*, a*, and b* variables. The Kruskal-Wallis test for all 3 variables was significant: L* component: chi-squared=293.76, df=5, $P<.001$; a* component: chi-squared=338.88, df=5, $P<.001$; b* component: chi-squared=333.75, df=5, $P<.001$. Given the significance of the overall test for group differences, the pairwise comparisons using nonparametric Dwass, Steel, Critchlow, Fligner tests were performed. The following groups were found to be significantly different from each other based on an experiment-wise Type I error of α=.05: L* component; all groups (P<.015) except group AM-1 versus group CNV-1 (P=.725) and group AM-2 versus group CNV-1 (P=.474); component a*: all groups were pairwise significantly different (all P<.001); component b*: all groups were pairwise significantly different (all P<.011).

The ΔE* values calculated using the CIE76 formula varied from 6.63 to 23.1 and using the CIEDE2000 formula from 3.43 to 10.21 between the CNV and AM groups, as well as within the AM subgroups.

DISCUSSION

Both null hypotheses were rejected, as significant differences were found for the L*, a*, and b* color dimensions between the CNV and AM groups and among the AM subgroups. It was not possible to measure the color dimensions for group AM-5 using the dental spectrophotometer, which could be explained by the color of the specimens being outside the dental color range.

A neutral grey background is frequently recommended for color matching in dentistry.[25,26,38,44] All specimens were measured following the same protocol, making the results comparable among the groups. When comparing the overall CNV and AM groups, significantly different L* values were found. Furthermore, the ΔE values using the CIE76 formulation varied from 6.63 to 18.06, with the lowest ΔE* value found between CNV-1 and AM-3 groups. As defined by previous studies, this ΔE* value can be considered an unacceptable color discrepancy.[23,24,38-40] When comparing the color differences among the different AM groups, ΔE* values varied from 10.68 to 23.09, which can be considered an unacceptable color discrepancy. Various authors have attempted to determine the acceptability of color discrepancy based on ΔE* values and have found that this value can vary from 2.72 to 6.8.[23,24,38-40] Based on the results of the present in vitro study, in all situations, an observer could easily detect color differences between all the interim restorative materials tested.

When the color differences were calculated with the CIEDE2000 formulation, all ΔE* values were consistently smaller than with the previous CEI76 formula (Fig. 3). Although there is no consistent pattern, the trend is for higher CIE76 than CIEDE2000 values. Such relatively large differences in CIEDE2000 values for corresponding small differences in CIE76 values may partly explain the wide range of perceptible and acceptable color difference thresholds reported by different authors[23,24,38-40]: some small changes in calculated CIE76 color differences were perceived as rather large leading to inconsistent responses and increased variability in reported results. The CIEDE200 color difference threshold value corresponding to the CIE76 6.8 acceptable color difference threshold would be approximately 4.6. While this value is not a substitute for the experimental determination of the perceptible and acceptable color difference thresholds in dental applications, an attempt to determine the acceptable color difference threshold is reported using the CIEDE2000 formula.

Significantly different L* values were found among the groups tested except for the comparison of AM-1 and CNV-1 (ΔL*=0.06) and the comparison of AM-2 and CNV-2 (ΔL*=0.2) groups. Therefore, most of the processes resulted in specimens of different brightness.

Greater positive values indicated higher red content in the color, and more negative values indicated higher green content. Both CNV groups tested presented significantly different a* values. The CNV-1 group was more greenish (-4.58 ±0.29) compared with the reddish CNV-2 group (4.37 ±0.78); however, the a* values of all the AM groups were within the range of the conventional group values. The a* value was the color dimension with the lowest color discrepancy among the CIELab components.

The b* value also varied among the groups. Higher positive values indicated a more yellow color, and higher negative values indicated a more blue color. The AM-2 group contained specimens with the lowest yellow characteristics, followed by the CNV-1, AM-3, AM-4, CNV-2, and AM-1 groups.

Similar materials were expected to have similar color properties, but significant differences were found between all the CIELab components. Custom shade guides for the AM interim materials tested could facilitate accurate shade selection and improve clinician to dental laboratory communication about these novel materials.[33-37]

The spectrophotometer model used in this study has been used in other studies to analyze color dimensions.[25,26,37] Paul et al[25] compared visual color matching methods using the Vitapan classical shade guide with color matching using the Spectroshade spectrophotometer. The authors achieved better color matches with the spectrophotometer than the traditional shade guide. Their study suggests that a device can adequately substitute for human vision when color matching. The crowns made using spectrophotometer matching were preferred in 90% of situations over the crowns made by visual matching. Da Silva et al[32] compared visual and instrumental shade matching methods. The authors found color matching by spectrophotometers to be more reliable than visual methods.[48-50]

Measuring specimen color was accomplished by holding the probe tip at 90 degrees to the specimen surface. However, minor angulations of the probe may have caused an edge-loss effect. In this effect, the illuminating beam scatters within the specimen and beyond the edge of the probe tip, especially when measuring a translucent specimen.[50] The edge-loss effect could contribute to inaccurate color measurement.

The present study had limitations, including the in vitro conditions for color measurements, the neutral grey background instead of a natural oral environment, the spectrophotometer selected, a geometric specimen instead of a natural tooth, and specimens of a different thickness than natural teeth. These factors could all amplify or reduce the color differences found. Further studies are recommended to assess the color matching capabilities of these new AM materials.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. AM procedures resulted in significantly different L* color values compared with conventional restorative interim materials.
2. Significant color differences were found among the AM interim material subgroups in all 3 color dimensions. These differences resulted in clinically perceptible and unacceptable color mismatch.
3. Except for the AM-1 and AM-2 groups in the L* color dimension, the AM interim materials tested were unable to match the conventional interim materials in any CIELab color dimension.
4. Color differences calculated using the CIEDE2000 formula were consistently lower than for their corresponding CIE76 values, resulting in an approximate acceptable color difference threshold of 4.6 with the CIEDE2000 formula.

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TABLE

Table 1. Conventionally (CNV) and additively manufactured (AM) interim materials tested

GROUP	MANUFACTURER	INTERIM MATERIAL	MANUFACTURING PROCESS	DEFINITION PROVIDED
CNV-1	3M ESPE	Protemp 4	Conventional procedures	Bis-acryl composite for single and multiple unit interim restorations.
CNV-2	Anaxdent	Anaxdent	Conventional procedures	PMMA acrylic resin.
AM-1	Detax	FreePrint Temp	AM	Monomer based on acrylic esters for manufacturing of 3D-printed crowns and bridges based on acrylic esters.
AM-2	Envisiontec	E-Dent 400	AM	Monomer based on acrylic esters. Class IIa CE Certified FDA-approved
AM-3	NextDent	C&B	AM	Class IIa CE Certified. FDA-approved
AM-4		C&B MFH	AM	Micro filled hybrid Class IIa CE Certified FDA-approved
AM-5	Stratasys	VeroGlaze - MED620	AM	Monomer based on acrylic esters.

Table 2. Means ±standard deviations of L*, a*, and b* components by manufacturer (group)

Group	AM-1	AM-2	AM-3	AM-4	CNV-1	CMV-2
L*	81.82 ±0.40	81.56 ±0.60	83.14 ±0.46	72.49 ±0.43	81.76 ±0.64	79.45 ±1.28
a*	1.14 ±0.467	2.42 ±0.72	-1.31 ±0.28	-1.59 ±0.26	-4.58 ±0.29	4.37 ±0.78
b*	16.46 ±0.54	39.52 ±0.54	27.99 ±1.16	27.28 ±0.32	33.59 ±1.47	24.93 ±1.63

AM, additively manufactured; CNV conventionally manufactured.

Table 3. Color component (L*, a*, b*) differences and color difference (ΔE*) values between different CNV and AM groups

Comparison groups	**Mean ΔL***	**Mean Δa***	**Mean Δb***	**Mean ΔE* CIE76**	**Mean ΔE* CIEDE2000**
CNV-1 and AM-1	0.06	5.72†	17.13†	**18.06**	9.32
CNV-1 and AM-2	0.2	7†	5.93†	**9.17**	5.83
CNV-1 and AM-3	1.38†	3.27†	5.6†	6.63	5.43
CNV-1 and AM-4	9.27†	2.99†	6.31†	**11.61**	7.42
CNV-2 and AM-1	2.37†	5.51†	8.47†	**9.36**	5.41
CNV-2 and AM-2	2.11†	1.95†	14.59†	**14.86**	6.62
CNV-2 and AM-3	3.69†	5.68†	1.94†	**7.43**	5.94
CNV-2 and AM-4	6.96†	5.96†	2.35†	**9.46**	7.50

Color differences considered unacceptable in bold (ΔE*>6.8)

†significant (*P*<.05) difference

Table 4. Color component (L*, a*, b*) differences and color difference (ΔE*) values between the AM groups. All pairwise differences significant (experiment-wise *P*<.05)

Comparison groups	**Mean ΔL***	**Mean Δa***	**Mean Δb***	**Mean ΔE* CIE76**	**Mean ΔE* CIEDE2000**
AM-1 and AM-2	0.26	1.28	23.06	**23.09**	10.21
AM-1 and AM-3	1.32	2.45	11.53	**11.86**	6.35
AM-1 and AM-4	9.33	2.73	10.82	**14.54**	9.04
AM-2 and AM-3	1.58	3.73	11.53	**12.22**	5.49
AM-2 and AM-4	9.07	4.01	5.31	**15.75**	8.69
AM-3 and AM-4	10.65	0.28	0.71	**10.68**	7.55

Color differences considered unacceptable (ΔE*>6.8) in bold

FIGURES

Figure 1. Specimen disks fabricated using conventional and additively manufacturing procedures after polishing sequence completed.

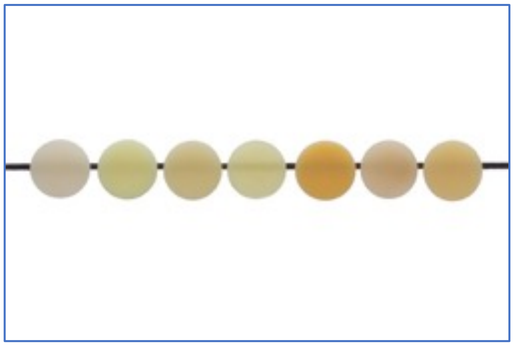
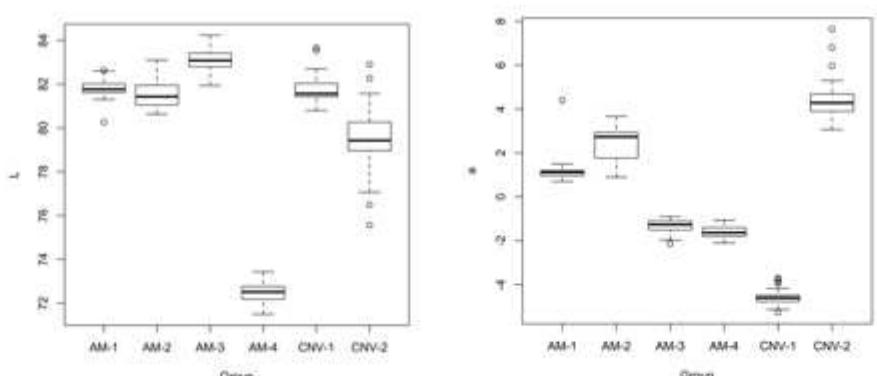


Figure 2. Minimum, maximum, interquartile range, medians, and outliers of measurements for AM-1 (FreePrint temp; Detax), AM-2 (E-Dent 400; Envisiontec), AM-3 (NextDent C&B; NextDent), AM-4 (NextDent C&B MFH; NextDent), and AM-5 (Med620 VEROGlaze; Stratasys), CNV-1 (Protemp 4, 3M ESPE), and CNV-2 (Anaxdent new outline dentin, Anaxdent) groups. A, L* component. B, a* component. C, b* component.



A B

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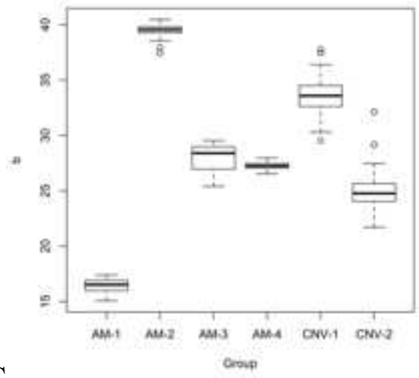

C

Figure 3. Scatterplot of CIEDE2000 color differences and CIE76 color differences for same pairwise group comparisons. Trend (solid line) fitted by eye using spline smoothing function smooth.spline in R with 0.8 smoothing parameter (spar). 6.8 threshold value (dashed vertical line) for CIE76 axis used to determine corresponding threshold (4.6, dashed horizontal line) on CIEDE2000 axis from fitted line.